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Improving the relevance and impact of water quality modelling for decision-making

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Abstract: Catchment managers often turn to computer-based water quality models to support catchment and natural resource management (CNRM). However, model use by managers is inherently problematic. Often-reported problems include inadequate or poor quality input data, miscommunication between scientists and managers, inappropriate treatment of model uncertainty and excessive model complexity or simplicity.

This paper reports on the methodological lessons learned from several CNRM projects in New South Wales, Australia. Six modelling project management problems that significantly impact on the utility of models in decision-making are discussed:

1. *Relevance and impact*. Model evaluation usually focuses on the technical *quality* of models*. Relevance* to the decision-making problem and *impact* on the decision that is made are more useful indicators of model effectiveness in decision-support.
2. *Methodological tension*. Disparate thinking amongst practitioners within knowledge communities can inhibit effective model use as much or more than disagreement or misunderstanding between scientists and managers.
3. *Model uncertainty*. Most treatments of uncertainty focus on quantifiable uncertainties and their assessment using sensitivity and uncertainty analyses. Conceptual uncertainties, which are difficult or impossible to quantify, often predominate.
4. *Excessive information gathering*. Timeliness is critical in decision-support. Excessive information gathering can contribute to 'information overload' and lead to 'analysis paralysis'.
5. *Inadequate information transformation*. The identification or creation of useful information in useful quantities and useful form may be more critical to CNRM than facets of information and knowledge management that receive greater attention, such as elimination of perceived barriers to knowledge *transfer* between scientists and managers.
6. *Vested interests*. The behaviour of individuals in a modelling project is often affected by incentives, biases and value-judgements that can contribute to poor modelling outcomes.

Guidelines on good practice in modelling often present a relatively narrow view of how scientific knowledge and modelling is used. Modelling challenges are usually framed as technical or technological problems that can be overcome by selecting appropriate models, using rigorous scientific procedures, and by open communication between managers and scientists. An implied expectation is that if a transparent and rigorous modelling process is used, science and modelling will be usable in CNRM.

Much research and development effort in the area of computer-based decision support is being expended on tool creation, data collection and management and on the resolution of technical issues that impact on the quality and reliability of the solutions generated by models and other decision support software. This paper argues that model effectiveness (i.e. the relevance and impact of the model on decision-making) can be improved by focusing greater attention on implementation methodology rather than technology. For example, effort should be focused on evaluating the appropriateness of modelling during program design and planning, and acknowledging and dealing with incongruity between the motivations, methodological preferences and epistemologies of individuals involved in the modelling project, especially where this occurs within rather than between knowledge communities.

Keywords: *Water quality modelling, decision-making, catchment management, watershed management.*

1. INTRODUCTION

Many catchment models and other computer-based decision-support tools have been developed, and these have been followed by numerous model evaluations, comparisons, protocols and guidelines (McNamara, 2007). However, in the last thirty years, there has been relatively little advancement in the ideas and methods used to assure the quality of modelling for decision-making (McNamara, 2007). Refsgaard and Henriksen (2002) noted that many model guidelines step the user through activities outlined in a protocol described by Anderson and Woessner (1992 p. 168), including: i) defining the purpose of the modelling study; ii) developing a conceptual model [based on field observations]; iii) developing a mathematical model; iv) selecting the modelling code; v) designing the model; vi) calibrating the model and undertaking a sensitivity analysis; vii) verification of the model [using historical data]; viii) prediction; ix) presentation of results; and x) post-audit [comparing predictions with observations]. Most protocols discuss technical issues at some length, but ignore or 'black box' important modelling project management issues, including setting appropriate modelling objectives, dealing with inherent and conceptual uncertainties and managing complexity, user expectations and confidence in model results (McNamara, 2007).

2. PREVAILING VIEWS

Where modelling project management issues are addressed in modelling protocols, they typically urge model users to select models that have an appropriate level of sophistication, ensure that managers and scientists collaborate in the selection and use of the modelling tool and the analysis of model outputs, and undertake sensitivity and uncertainty analyses.

In relation to model sophistication, a general view is that model complexity should be based on objective criteria relating to the nature of the problem to be resolved and the availability of data and knowledge. "*Horses for courses*" and "*simple, but not too simple*" are idioms often articulated by both modellers and managers to convey the need to match the model to the problem situation (see McNamara, 2007).

Engagement of catchment managers and other stakeholders in modelling is posited as a way of fostering creative and relevant solutions, clarifying modelling needs and managing end-user expectations. A common view is that uncertainties, assumptions and limitations of models and their outputs should be documented by modellers and borne in mind by managers when using models to guide decisions. Protocols typically stress that modelling processes need to be transparent, allowing managers and others (e.g. steering committees and affected stakeholders) to scrutinise model assumptions. They generally argue that non-experts should be able to understand the basic components and limitations of models that support their decisions, and that 'black boxes' and very complex models should be avoided.

With respect to uncertainty, protocols commonly argue that model users should know the level of uncertainty associated with modelling results. Quantifying uncertainty is said to help managers know when there is a need for more research, and when management interventions based on model outputs are justifiable.

3. NEGLECTED ISSUES

The views above reflect normative assumptions and provide model users with logical guidelines for identifying good solutions amongst a range of feasible decision choices. However, managers typically exhibit 'bounded rationality' (Simon, 1957) and the decisions they make are constrained by culture, heuristics, knowledge limitations and cognitive capacity. Few protocols adequately address these behavioural constraints. In an action research project involving a NSW CNRM agency, McNamara (2007) identified six inter-related modelling project management issues that have the potential to inhibit successful model application and yet are not adequately elucidated in most modelling protocols. These are presented in this section, with minor modification based on experience in other CNRM modelling projects.

3.1. Evaluate alternative models using *relevance* and *impact* criteria

Catchment models are usually evaluated using technical *quality* criteria such as model accuracy (i.e. 'history matching'), repeatability of modelling, transparency of the data and assumptions and the academic credentials of the model or its builder (i.e. 'peer review'). However, these criteria are more pertinent in academia than in CNRM. In CNRM, model suitability is better indicated by the contribution of the model to stakeholder acceptance of the decisions that are made (i.e. 'legitimacy'), which is only partly related to the technical quality of the analysis. Additional criteria are required for evaluating models as decision support tools. Broadly, these additional criteria are *relevance* of the proposed model to the decision-making problem and, more importantly, the likely *impact* of modelling on the decision that is made. Such criteria help position prospective models in the CNRM context. A heuristic evaluation checklist that includes a list of CNRM-focused criteria is proposed in Table 1.

Table 1. A heuristic evaluation checklist for computer-based decision support tool selection.

Desirable Criterion	**Definition**
Indicators of *Quality*: The tool provides the user with high quality decision advice	
Accurate	Input data, assumptions/algorithms and outputs have been peer-reviewed and tested and shown to be accurate to within reasonable limits
Acknowledges uncertainty	The impact of uncertainty on the result of the assessment is clear and key sources of uncertainty (e.g. potentially inaccurate inputs and/or flawed assumptions) are identifiable
Repeatable	The tool provides a structured and repeatable assessment process
Accountable	Operation of the tool is documented so that the assessment can be reviewed or audited
Transparent	There are no hidden or unexplained variables, algorithms or assumptions
Reputable	The tool was developed by a reputable tool-builder and/or is endorsed by a competent authority
Supported	The tool is supported by a user/technical manual, effective help screens and a help desk for email or telephone support. Training is available
Mature	The tool has a track-record of successful use and is neither untested nor out-dated
Indicators of *Relevance*: The tool is fit for purpose	
Accessible	The tool is available when needed
Contextual	The tool harmonises with existing decision-making frameworks and processes and is consistent with the socio-political, economic and environmental context in which the decision is being made
Scale-appropriate	The temporal and spatial scale of the tool is relevant to the decision that needs to be made, sensitive to impacts at larger and smaller scales and commensurate with the resolution and accuracy of input data
Compatible	The tool is compatible with existing data, databases, hardware and software
Economical	The tool can be deployed cost-effectively
Feasible	The assessment can be undertaken using available data, resources and expertise
Understandable	The interface is user-friendly and the tool is not unnecessarily complex
Timely	The assessment will be completed within a reasonable time-frame
Fast	Processing speeds are reasonable
Flexible	The tool can be modified to suit other decision-making needs
Indicators of *Impact*: The tool will influence or legitimise decisions	
Promotes innovation	The tool stimulates thought and enquiry that can assist with creative aspects of problem definition and the identification of innovative solutions
Iterative	The tool can be used to test alternative assumptions or scenarios
Integrative	The tool helps the user acquire, sort and analyse data, information and knowledge from diverse sources
Informative	The tool provides users and/or stakeholders with insights over and above those that could be gained using existing knowledge or tools
Acceptable methods	The methods are acceptable to stakeholders and relevant staff (e.g. senior management who authorise management interventions and operations staff that implement the actions)
Deliberative	The assessment deals explicitly with divergent views and helps build consensus
Reusable	The tool can be reused and forms part of your normal business processes

3.2. Manage methodological tension

Much is written about barriers to communication *between* disciplines, notably scientists and managers, which inhibit the usefulness of science or modelling in CNRM. An under-recognised problem in protocols is that there is often disagreement *within* disciplines about the way problems should be formulated and analysed. Models are often posited as tools that can be used to structure thinking around a decision-making problem (e.g. McNamara and Cornish, 2004) but they can also foster disagreement and debate (McNamara, 2007).

For example, in relation to nutrient modelling in catchments, efforts to simulate nutrient fluxes are hampered by "*a poorly defined conceptual model of the nutrient export process*" (Young *et al*., 1996 p. 180). Experts referring to the same study area can have different views on the importance of first flush and variable source areas, the usefulness of the curve number as a method for determining runoff rates, the relative importance of streambank and gully erosion and the use of loads or concentration as the preferred method for determining nutrient source strengths and delivery to streams. More fundamentally, there may be disagreement about the reliability of remotely-sensed spatial data and methods used to discretise land-use and management units for analysis (McNamara, 2007). Catchment-scale water quality modelling for policy- and decision-making is particularly problematic because of inherent complexities and uncertainties and because, as is the wont of the manager when dealing with a multiplicity of scales, "*advocating a single perspective that encompasses everything in a system becomes increasingly difficult – plus less effective* (Poch *et al*., 2004 p. 858).

For many CNRM decision problems there will be a range of feasible analytical techniques. Context-driven judgments will need to be made about the choice of evaluation method, the selection of inputs, the resolution and scale of the analysis, the degree of stakeholder and expert participation and the type and level of results that are reported. Experts often have qualitatively different biases, philosophies and personal experiences, leading to methodological tension when a modelling project is posited, executed or reviewed. Even within the mind of a model user, there may be tension between their aspirations for detail, precision and certainty and the constraints imposed by data quality and quantity, time, expertise and resources. The result is often dissatisfaction with models, rejection of model outputs and a call for more and better data or more and better modelling.

Transparency, although offered as a partial solution, can expose qualitatively different mental models of individuals involved in a modelling project and quantitative disagreements about the relative importance of key model parameters and processes. Collaboratively resolving such differences can be difficult because individuals often have different modes of cognition, analysis and intuition. Mumpower and Stewart (1996) argue that reaching consensus in such circumstances requires experts to leave entrenched positions and agree to use a common mode of thought. However, they argue that when individuals' organising principles are different, "*methods for diagnosing and treating disagreement are poorly understood*" (ibid p. 191). The absence of such methods in modelling protocols may reflect the inadequacy of current 'analytic-deliberative' processes (Brewer and Stern, 2005).

3.3. Manage uncertainty

Uncertainty is problematic for managers because it erodes confidence in, and threatens the legitimacy of, their decisions. Most guidelines state or imply that managers lack confidence in models because of inconsistency in approaches and miscommunication between modellers and managers. However, these issues are also intradisciplinary. Inconsistency amongst experts (managers and scientists) is at least partly due to imperfect domain knowledge and different ways that domain experts perceive CNRM problems. Moreover, managers in some CNRM agencies have a background in science and understand model limitations and their familiarity with these limitations may, in practice, contribute to their lack of confidence (Mackenzie, 1999).

Scientists and managers have a poor record of dealing with the model uncertainty (Pielke *et al*., 2000). A common overly-simplistic view is that uncertainty is the result of poor-quality science and inevitably leads to controversy, indecision and inaction. Managers often try to "*expel*" uncertainty before making a decision, through demands for more and better research, data collection and modelling (van der Sluijs, 2005), potentially resulting in unacceptable delays in policy-development and management action. Model uncertainty should not be a cause for management inaction when the benefit of a rapid response outweighs the benefit of inaction or delay. Most guidelines argue that uncertainty information can be used as a tool to help decide when management intervention is justifiable and when more research is needed. To this end, protocols often advocate the use of sensitivity and uncertainty analyses. Although useful, these analyses do not deal well with inherent and conceptual uncertainties. Tools such as PRIMA (Pluralistic fRamework for Integrated uncertainty Management and risk Analysis), the NUSAP notational system (Numeral Unit Spread Assessment Pedigree) and the "*Checklist for Model Quality Assistance*" offer innovative ways of managing and communicating uncertainty that, especially in the sphere of policy development and management, can complement conventional approaches (see van der Sluijs *et al*., 2004).

In any case, convincing arguments can be made for action in the absence of certainty. The precautionary principle, for example, is often posited as an appropriate response to uncertainty when the risk of indecision and inaction are high. A less doctrinaire 'no-regrets' approach can be used to legitimise decisions when the secondary benefits of a proposed management action are likely to outweigh the cost of the action, even if the underlying assumptions that formed the basis of the decision are eventually proved wrong. Adaptive management, where decisions and actions are viewed as management experiments, can be used to reduce a perception that policy-makers or managers are acting recklessly or in ignorance. More fundamentally, prospective model-users can frame problems such that the aim of modelling is to find a solution that is acceptable rather than optimal (ie 'satisficing').

3.4. Limit information gathering

Catchment and natural resource managers are increasingly encouraged to make decisions using best available science and, more recently, multiple lines and levels of evidence. However, if these approaches are poorly executed, or if the manager is particularly risk- or conflict-averse, information gathering can be excessive, information overload can ensue and decision-making can become paralysed. So-called analysis paralysis is a common problem in decision-making and is often expressed in relation to catchment modelling (McNamara, 2007). A potential flow-on effect is that a vigorous pursuit of more or better data and knowledge may be falsely interpreted by critical stakeholders as an indication that the scientific basis for decision-making is inadequate (Reckhow, 1994).

Ongley (1999) described the 'data paradigm', in which institutions seek more and better data without recognising that natural systems are so highly variable that monitoring programs may be unable to capture this variability. Some uncertainties are very difficult or impossible to resolve with currently available data and knowledge. Information gathering, even with best available science, may amount to little more than opinion gathering. For instance, Letcher *et al*. (2002) modelled sediment and nutrient exports in several catchments across Australia using four different models. Although each catchment was selected because it had the best available data in its respective State or Territory, the modellers reported that there were insufficient data to calibrate any of the models in most catchments, or provide a "*robust estimate*" of annualised loads using monitoring data and direct estimation techniques. They were subsequently unable to conclude which model provided the most accurate prediction. In such cases, decisions about model parameters and processes become guesswork (Reckhow, 1994). It is ironic but understandable then that although there is a relative dearth of model-ready data, there are a plethora of models (see McNamara, 2007). Many models represent their developer's best guess about the way systems operate.

Another reason to constrain information gathering is that, even with best available science, institutional, social and economic considerations can predominate decision-making. For example, managers must conform to the demands of funding bodies (e.g. compulsory reporting and spending time-frames and funder priorities) and are constrained by landholders' willingness to participate in CNRM. More broadly, resources allocated to CNRM are constrained by socio-economic considerations, including calls for fair or equitable distribution of CNRM effort (or cost burdens) across regions and industries, competing demands for public funds to be allocated to other causes, or simply changes in policy and management focus. For example, Land and Water Australia (Schofield, 2005) found that "…*the impact of CMSS* [Catchment Management Support System] *was reduced partly due to a general shift in the topical issues regarding water quality from algal blooms in the 1990s to environmental flows and salinity and then to water sharing and native vegetation and land management that affect water quality. This changing situation, together with catchment management structural changes, meant that the implementation of plans developed from the use of CMSS were significantly delayed*" (p. 3).

3.5. Focus on information transformation

When framing a problem for analysis, managers need to determine what constitutes evidence and seek out tools that help them consolidate relevant information and knowledge and avoid information overload. In modelling protocols, evidence is usually construed to mean *robust* and *defensible* information about current or future system behaviour (i.e. estimates or predictions). However, models are simplifications of reality that do not attempt to represent all of the elements and interactions that make up CNRM problems. Searching for evidence using predictive models may constrain creativity, limit the choice of feasible solutions, and "*promote the attitude of bending the task to suit the model*" (Barnes, 1995 p. 748).

To maximise the chance of a successful outcome from modelling, managers should consider the ability of the model and modeller to communicate and translate scientific information into a usable form. In the design and planning phase of a CNRM program, managers can structure the search for evidence by viewing modelling as a sub-process in a broader ex ante evaluation framework that includes all known elements and interactions that need to be considered. The appropriateness of modelling within the evaluation framework can then be assessed using techniques such as needs analysis (Walker and Johnson, 1996) and program logic 'modelling' (Funnell, 1997).

3.6. Understand and manage vested interests

The different actors engaged in modelling for decision-making (e.g. organisations, model developers, analysts, managers/policy-makers and community stakeholders) are subject to unique sets of influences that can negatively impact on the outcomes of catchment modelling. To deal with such conflicts, managers need to be aware of the existence of bias and self-interest and clarify the role of actors in a modelling project - and the role of modelling itself. Some examples are discussed below.

Agencies and departments within organisations may want to preserve their status or importance and, as a consequence, be unwilling to share data, resources, knowledge or decision-making authority with other organisations, departments or stakeholders.

Individual managers or groups may feel that they must, "…*present options with confidence and certitude to maintain credibility with political decision makers and players from other agencies*" (Walters, 1997). Risk- or conflict-averse managers may perceive a benefit in avoiding decision-making when faced with model uncertainty, such as when decisions may be challenged or if a manager might suffer professionally if predicted outcomes are unrealised. The manager may therefore see model uncertainty as an opportunity to avoid action, or see modelling as a chance to devolve responsibility for a contentious decision to modellers.

Competitive tendering of research and modelling projects can encourage vigorous self-promotion and encourage model developers or analysts to over-sell the capabilities of the models they develop or use, or to promote particular models based on convenience (e.g. prior experience) rather than suitability. At the conclusion of a modelling project, modellers may be inclined to over-emphasise ambiguity and uncertainty to press for more research, funding and modelling. Similarly, disaffected stakeholders and special interest groups can exploit and exaggerate model uncertainty to stymie decision-making or further their own agendas.

In CNRM, information that is integrative and well-tested is typically more useful than highly disciplinary, experimental and less well-tested theories. By contrast, scientific recognition is typically achieved through focused disciplinary research. Also, for most policy issues, many factors that are uninteresting to scientists come into play. Findlay (1992) argued, "*scientists are either unwilling or unable (or perhaps both) to address themselves to the larger social and political implications of their work*" (p. 122). He argued that scientists are more comfortable in the role of investigating and reporting "*what is*", but are largely unwilling to "*help decide what should be*" (p. 123), and regard this role as one that is outside their purview. Notwithstanding recent recognition of the importance of integration in CNRM, integrative CNRM approaches continue to be impeded by institutional, epistemological and other barriers (Tress *et al*., 2007).

4. CONCLUDING REMARKS

Data and scientific understanding, although limited, are not the key limiting factors in the successful management of most CNRM problems. In relation to management of nutrient pollution in the USA, Brezonik and Renwick (2003 p. 151) argued that, "*the principal limiting factors seem to be related to the socio-cultural, economic, and political environments in which technical solutions need to be implemented*". They suggested that limitations in existing legal authorities, economic constraints, conflicting attitudes and priorities among key stakeholders, and the highly disaggregated nature of the pollutant contributors have slowed the pace of progress in solving diffuse pollution problems. Whilst monitoring and quantitative scientific knowledge of the drivers of diffuse pollution in Australia are not as comprehensive as they are in the USA (Young *et al.,* 1996), many of these limiting factors also predominate in Australian contexts.

The needs of managers are not well-served by current modelling protocols because the protocols do not adequately address the key limiting factors. Although generally robust in relation to technical and technological aspects of model use – areas that are of interest to scientists – they are typically weak in key areas relating to implementation methodology. Specific areas of weakness include model evaluation heuristics, conceptual uncertainty, information 'transformation' and managing methodological tension and mixed and competing motivations of individuals within knowledge communities.

Some inter-related solutions are proposed, and these can be incorporated into future protocols: The appropriateness of models and modelling can be evaluated using needs analysis and program logic modelling; prospective model users can evaluate models against criteria that indicate contextual relevance and the likelihood of an impact on decision-making or the legitimacy of decisions; further attention can be given to analytic-deliberative processes; innovative approaches can be used to evaluate, communicate and manage uncertainty and, in particular, conceptual uncertainty; and decision-making frameworks can be used that are tolerant of uncertainty.

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